A Compact Gas Spectroscopy Sensor System Based on a Voltage-Frequency-Tuned 245 GHz SiGe Transmitter and Receiver

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Abstract— **A compact gas spectroscopy sensor system based on a 245 GHz transmitter (TX) and receiver (RX) fabricated in SiGe technology is presented. The frequencies of the TX and RX are tuned by applying external voltages at the voltage-controlled oscillators. For 2f spectroscopy, a frequency modulation is also applied at the TX. As a result, methanol spectra are presented, that exhibit a high signal-to-noise ratio of up to 560 and an acquisition time as short as 39 s, respectively.**

I. INTRODUCTION

TERAHERTZ/MM-WAVE spectroscopy is a powerful tool for the identification of many gases due to their rotational transitions. Possible applications are envisaged e.g. in medicine as a detector for volatile organic compounds (VOCs) in human breath [1]. These can be used as indicators for many metabolic processes or diseases [2]. The compounds can be identified e.g. by a principal component analysis of the spectroscopic data [3]. We report on a sensor system based on 245 GHz transmitter (TX) and receiver (RX) integrated chips fabricated in 0.13 µm BiCMOS SiGe technology of IHP. In an earlier work, the TX and RX frequencies were tuned by external integer (N)-phase-locked loops (PLL) with external reference frequency generators [4]. Here, the frequencies are tuned by directly applying voltages at the VCOs. Thus, no external reference frequency generator is necessary for the tuning. Device-specific voltage-frequency-calibrations were performed by simultaneously measuring the voltage at the VCO and setting the frequency with the external PLL.

II. EXPERIMENTAL SETUP

The TX consists of a 120 GHz push-push voltage-controlled oscillator (VCO) with 1/64 divider, a power amplifier, a frequency doubler and an integrated antenna fabricated by localized backside etching (LBE) [5]. The heterodyne RX with an 18 dB conversion gain includes a differential LNA, a 120 GHz push-push VCO with 1/64 divider, an LO-buffer, a 90° differential hybrid, an active subharmonic mixer, and an on-chip antenna [6]. Both, TX and RX were fabricated in 0.13 µm BiCMOS SiGe technology of IHP. The schematics of the 245 GHz TX including the VCO, the power amplifier, the frequency doubler, and the integrated antenna are shown in Fig. 1.

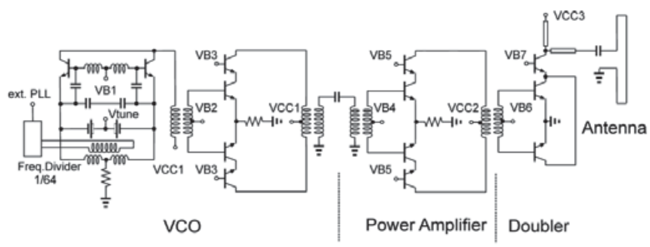

Fig. 1. Schematics of the 245 GHz TX with 120 GHz push-push VCO, 1/64 divider, power amplifier, frequency doubler, and integrated antenna.

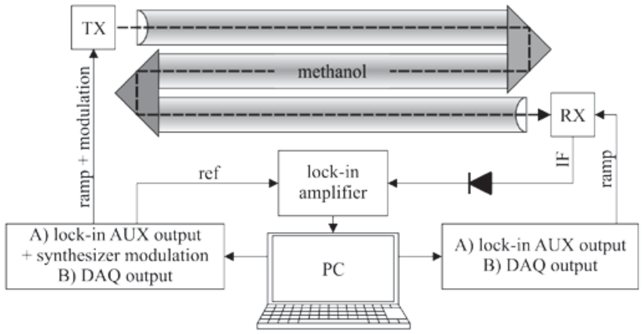

Fig. 2. Schematics of the experimental setup. The ramp and modulation signal for the TX and RX are either generated (A) by a lock-in amplifier output and a frequency generator or (B) by a data acquisition (DAQ) module.

The experimental setup of the compact gas spectroscopy sensor system is shown in Fig. 2. The gas cell with a 1.9 m path length is folded into three segments in order to allow for a compact setup. The input and output high-density polyethylene (HDPE) windows of the gas cell serve as lenses with a 40 mm focal length for collimating the beam and focusing it onto the RX. The gas cell, the vacuum pumps, as well as the TX and RX are placed on a portable breadboard with dimensions of 75 cm x 45 cm. Linear frequency ramps with a constant frequency offset are applied to the TX and the RX by directly applying nonlinear voltage ramps without any PLLs or frequency synthesizers. For that purpose, a voltage vs. frequency calibration was performed before the measurements. As a result, with nonlinear voltage ramps between 0.3 V and 2.9 V, the TX and RX can be tuned linearly in frequency from 234 GHz to 252 GHz and from 237 GHz to 255 GHz, respectively (see Fig. 3). The intermediate frequency (IF) signal of the RX is rectified by a Schottky diode and measured by the lock-in amplifier. For phase sensitive lock-in detection, a modulation was added to the TX frequency ramp. The ramps were either realized by an analog output of the lock-in amplifier (setup A) or by a data acquisition (DAQ) device (setup B). In setup A, the modulation for the TX was provided by an external frequency generator and added to the ramp by a bias-tee whereas in setup B, the superposition of ramp and modulation was generated by the DAQ only.

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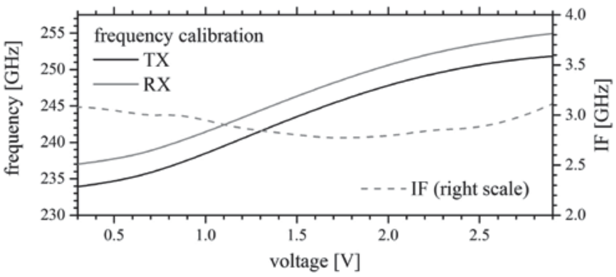

Fig. 3. Frequency vs. voltage calibration of the TX and RX. The frequency was tuned with an external reference PLL for the calibration.

III. Results

The black line in Fig. 4 shows a methanol spectrum measured at a pressure of 12 Pa. The TX was tuned from 238 GHz to 251 GHz whereas the RX had a constant offset of 400 MHz above the TX. With a step width of 500 kHz and the corresponding step time of 45 ms, a total acquisition time of 1160 s was achieved. The lock-in amplifier (time constant 28 ms) was locked to the 2nd harmonic (2f spectroscopy) of the 600 kHz frequency modulation, which was added to the TX by a frequency generator. Approximately 100 absorption lines are detected in accordance to the simulated data shown in light grey at the bottom. However, with respect to the calibration, the measurement revealed a slight displacement of the frequency axis of about 250 MHz which was corrected in the graph. For the reference line at 243.92 GHz (line strength: S = $4.8 \cdot 10^{-23}$ cm/mol) an SNR of 560 was obtained. The characteristic 2f line shape as well as the line width is in good agreement with the simulation as can be seen in the inset.

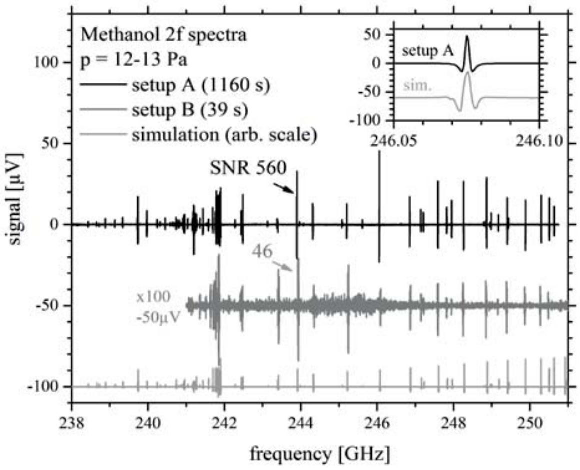

Fig. 4. 2f spectra of methanol measured by voltage frequency-tuning of the TX and RX VCOs. The inset shows a snippet of a single absorption line (setup A) in comparison with a simulation (sim.).

The dark grey line shows a measurement taken within only 39 s at a pressure of 13 Pa. In that measurement, the frequency tuning voltages as well as the frequency modulation were provided by one single 24 bit analog output module thus making the setup more compact since no external frequency generator was used. The RMS noise of the output voltage was determined to 60 μV which corresponds to 100 kHz – 600 kHz with respect to the frequency calibration. Standing waves that occurred between the TX and RX boards were removed by high pass filtering of the data. The result exhibits a smaller SNR (46 @ 243.92 GHz) due to the shorter acquisition time and the lower modulation frequency of 12.8 kHz.

IV. Conclusion

A compact gas sensor system based on a 245 GHz SiGe TX and RX was demonstrated. Methanol spectra were presented with a high SNR of up to 560 and an acquisition time of 39 s for a 10 GHz spectrum, respectively. In the next steps, the dimensions of the setup will be further decreased. This includes e.g. the replacement of the hardware lock-in amplifier by software lock-in detection. Furthermore, the frequency tuning will be realized by a fractional N-PLL and a fixed reference frequency. Thus, the frequency resolution will be improved without any external frequency synthesizers.

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